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Time-of-Day of Peak Tides in a Mixed-Tide Regime

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ABSTRACT

The occurrence along the California coast of highest-high tides in the morning during winter and in the afternoon during summer is explained as the interaction of the two largest tide constituents (M_2 and K_1). This seasonally oscillating, loose phase locking of the time of day of peak high tides is a consequence of the area's mixed-tide regime, and an example of how tide characteristics of mixed-tide regions differ from those in areas with predominantly semi-daily tides. The observed pattern of peak high tides has notable consequences for coastal storm-preparedness, nearshore sedimentation cycles, and the distribution of inter-tidal organisms.

Keywords: tide, extreme tide, California

INTRODUCTION

ALONG THE PACIFIC COAST of North America, the highest-high tides of each year occur near the summer and winter solstices, as demonstrated by Zetler and Flick (1985a), who tabulated the monthly peak high tides for the California coast for 1982-2000. Zetler and Flick (1985b) found several other interesting features, including a prominent 18.61-yr lunar-node cycle, and periodic enhancements due to the 4.4-yr "passage of the longitude of (lunar) perigee past the equinoxes" (Cartwright 1974), that distinguish the mixed-tides found along the West Coast from the mainly semidiurnal tides of the East Coast.

Along the California coast, the higher-high tides occur in the morning (defined as midnight to noon) during winter, and in the afternoon (noon to midnight) during summer. The times of lower-low tides are reversed. This loose, seasonally varying phase locking of the peak tides to the time of day represents another property of the region's mixed-tide regime.

Table 1. Tidal constituents referred to in the text

Name[1]	Description[2]
M_2	Represents the rotation of the earth with respect to the moon
K_1	Lunisolar diurnal constituent, acts with O_1 and P_1
O_1	With K_1 expresses semi-monthly effect of lunar declination (tropic tides)
P_1	With K_1 accounts for semi-annual effects of the sun's declination (tropic tides)
N_2	Accounts for variation in angular speed of the moon caused by elliptical orbit
S_2	Represents the rotation of the earth with respect to the sun

1) Subscript 1 indicates a diurnal tide constituent with a period near 24 hr; subscript 2 indicates a semidiurnal constituent with a period near 12 hr.
2) Hicks (1989)

This paper demonstrates that the essential features of the seasonal phase locking of times of high and low water off California is caused by the interaction of the two largest tide constituents, M_2 and K_1 (Table 1). M_2 is the principal lunar constituent. K_1 is the lunisolar diurnal constituent that, together with O_1 and P_1, accounts for the diurnal inequality (and at extremes, diurnal tides), which is caused by the declination of the moon and the sun, and is a key constituent of mixed-tide regimes. The underlying seasonal pattern of the time-of-day of high and low tide is provided by K_1, whereas M_2 smears the time of day of each successive higher-high tide through the morning hours in winter, and through the evening hours in summer.

IMPORTANCE OF TIDE TIME-OF-DAY

Daily and seasonal patterns in the times of high and low tide have been noted along the Pacific coast and on part of the Baja Gulf of California coast. Inman and Filloux (1960) recognized that when the peak higher-high tides occurred at the same time as the maximum afternoon sea breezes and associated wind-wave intensity on the northwestern shore of the Gulf of California, the combined high water and wave activity produced a periodic beach sedimentation cycle. Inman, et al. (1966) described the seasonal patterns of peak tides along the Pacific coast of central Baja, observing that dune fields at Guerrero Negro were regularly flooded during the afternoon in summer, the time of strong sea breezes, but in the morning in winter, when there was no wind. This pattern left markers in the dunes that were used to measure dune migration.

Hedgpeth and Hinton (1961) noted that the lowest mid-winter tides along the Pacific coast occurred in the afternoon, whereas the mid-summer ones always occurred in the morning. Curiously, they stated that the highest (and lowest) tides occurred "during the solstices of spring and fall (March 21 and September 21)," which should read "summer and winter (June 21 and December 21)," as demonstrated by Zetler and Flick (1985a,b). Piper (1984) summarized the effects of exposure times, length of exposure and the time of day of the low tides in summer and winter on the zonation of an intertidal mollusc. Flick and Badan-Dangon (1988) pointed out that the occurrence of higher-high tides in the morning in winter on the California coast could hinder storm preparations, because these must be carried out at night.

PACIFIC COAST TIDAL PATTERNS

The Pacific coast of North America has a mixed-tide regime, with a pronounced diurnal inequality, owing to the fact that the amplitude ratio of the diurnal tidal constituents to the semidiurnal ones is about 0.8. The six tide constituents M_2, K_1, O_1, P_1, N_2, and S_2 (Table 1) contain essentially all the information (about 98% of the variance) describing tide conditions at Los Angeles, California, herein used to illustrate the peak tide patterns. The typical daily tide curve in California proceeds from higher-high to lower-low stage in 6 to 8 hours, and then rises back through lower-high and higher-low stages during the rest of the tidal day. This pattern is caused by the specific phase and frequency relationships among M_2, K_1, and O_1, as detailed by Zetler (1959).

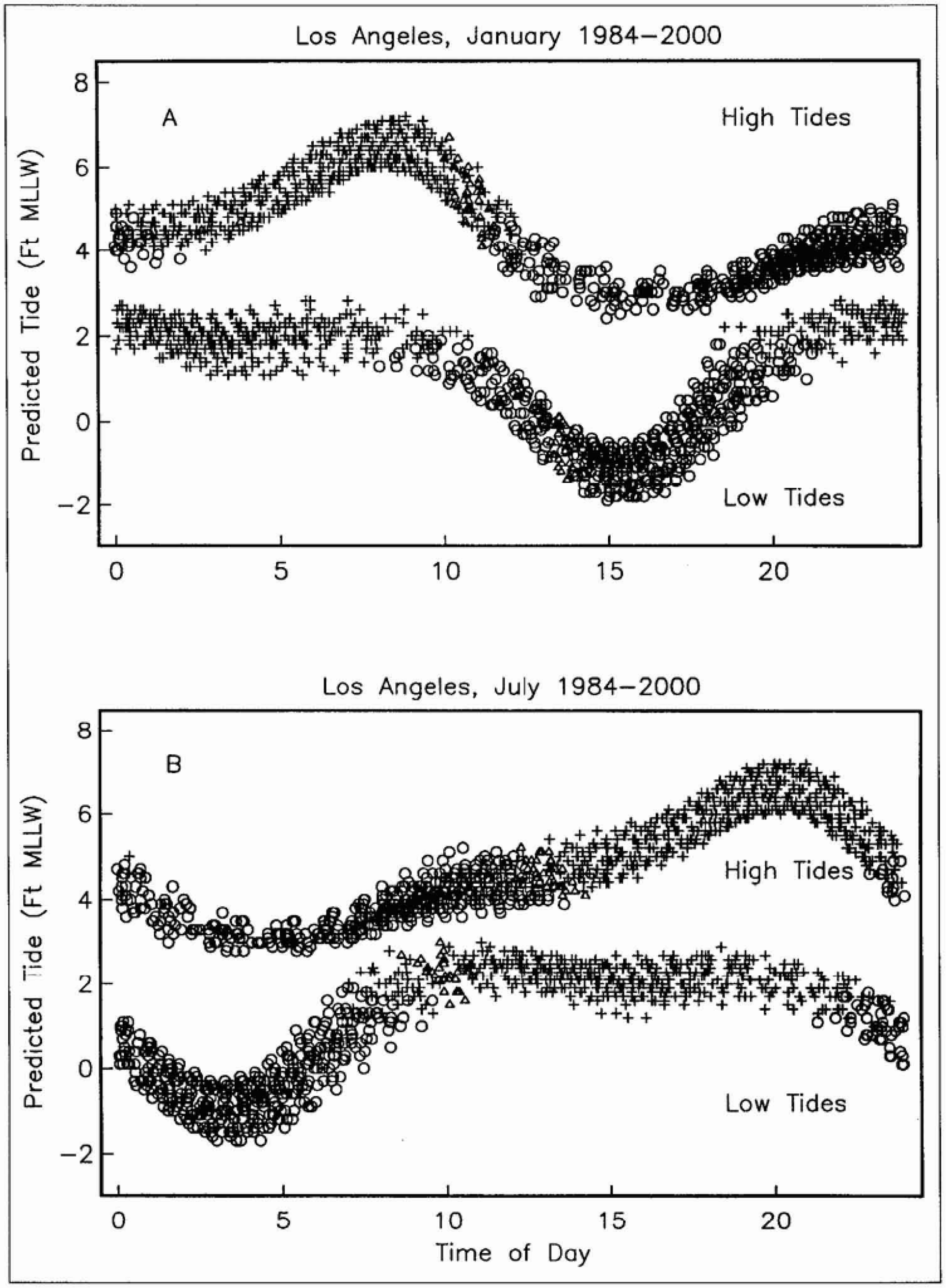

Figure 1. Predicted height versus time of day for all higher-high (crosses), lower-high (circles), higher-low (crosses), and lower-low (circles) tides at Los Angeles during January (A, upper), and July (B, lower), 1984-2000.

Figure 1A shows a plot of the heights vs. times-of-day of all high and low water tide predictions (as labeled) at Los Angeles during January for the years 1984-2000, and Figure 1B shows the same information for July. The data were obtained for the extreme tide study of Zetler and Flick (1985a,b) from the National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS), and represent their standard tide-prediction product. The crosses in each plot indicate the higher-highs or higher-lows (respectively), and the circles indicate lower-highs and lower-lows. The few triangles depict days with only one high or low tide. Inspection of Figure 1 shows that the highest high tides always occur in the morning in January, and in the evening in July, whereas the pattern for the lowest tides is reversed. Similar plots for other months (not shown) reveal a gradual shift of time-of-day pattern from one to the other.

As shown in Figure 2, the essential features of the seasonal phase locking of times of high and low water are contained in the two largest constituents, M_2 and K_1, which contain about 80% of the predicted tide variance in California. M_2 has an amplitude of 51 cm at Los Angeles, and K_1 has an amplitude of 34 cm.

SEASONAL PATTERN DUE TO M_2 AND K_1

The fact that the higher-high tides occur in the morning in winter, and in the evening in summer, is primarily determined by the K_1 component of the tide, which happens to peak at about 0500 in winter, and at about 1700 in summer in southern California. The frequency of K_1 differs from 1 cpd (cycle per day) by only 1 cpy (cycle per year). As a consequence, the time of high water of K_1 progresses steadily earlier by about 4 minutes each day in the intervening months. The constituent P_1 behaves in a similar manner, also differing in frequency from 1 cpd by only 1 cpy, and having early morning highs in winter and early evening highs in summer. This reinforces the tendency for the observed seasonal phase locking. M_2 differs in frequency from 2 cpd by 2 cpm (cycles-per-month). M_2 peaks show no monthly or seasonal time-of-day preference, because daily times of high and low water progress by the standard (semidiurnal regime) 50 minutes per day. The contribution of M_2 to the observed pattern is to shift each successive daily higher-high water by about 50 minutes later per day, without changing the seasonal pattern.

Figures 2A and C respectively show the time of day of the predicted higher-high tide (crosses), and lower-low tide (circles) for January and July 1987 at Los Angeles, using all 21 tide constituents published by NOAA/NOS. For practical purposes, these predictions accurately represent the actual water levels. The selection of 1987 is arbitrary and does not affect the conclusion, since the pattern is similar every year. Figures 2B and D show the same information based on tide predictions using only M_2 and K_1. The correspondence between Figures 2A and B, and 2C and D leads to the conclusion that together, M_2 and K_1 account for the time-of-day pattern of the peak tides, and its seasonal variation. Neither M_2 nor K_1 alone (not shown) explain both the observed seasonal pattern and day-to-day higher-high tide time shifts, although K_1 (alone or with P_1) does determine the underlying seasonal variation.

The local tidal constituent phases are coincidental, a consequence of the response of this part of the Pacific Ocean to the tidal forcing. In fact, the tidal time-of-day relationships slowly shift later with distance north as a consequence of the northern propagation of the tide along the West Coast. As Piper (1984) noted, along the Washington coast the respective higher-high and lower-low waters occur 7 or 8 hours later than in southern California.

As Zetler and Flick (1985b) found with their effort to elucidate the height of peak high tides in California, the mixed-tide regime, with its substantial diurnal components, is responsible for additional effects not seen in largely semi-diurnal regions, such as the East Coast of the U.S. In particular, the solar declinational effects expressed by the constituents K_1 and P_1 are primarily responsible for the observed seasonal pattern of the time-of-day of the higher-high tides. The details of the time-of-day relationship are modified by M_2 to produce the observed pattern of loose phase locking.

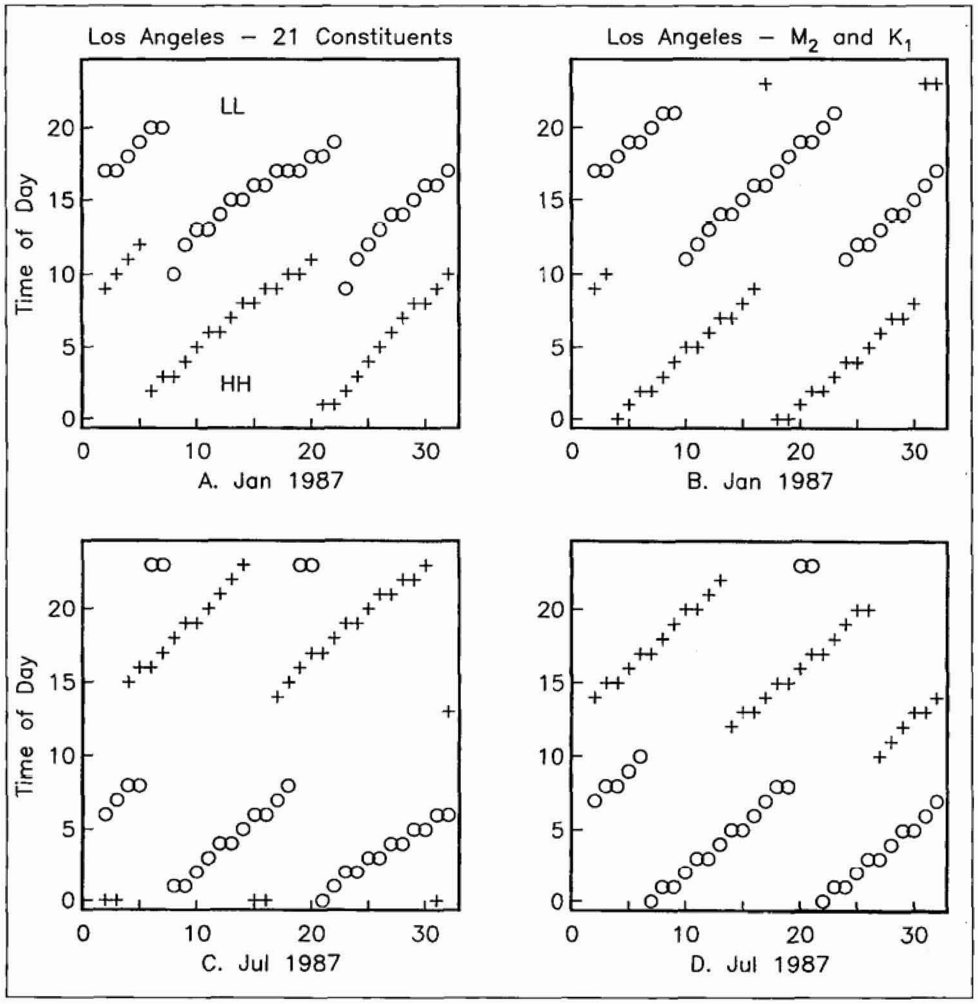

Figure 2. Time of day versus day of month for higher-high (crosses) and lower-low (circles) tides at Los Angeles for January 1987 (A, B, upper panels), and July 1987 (C, D, lower). Left panels (A, C) were predicted using 21 constituents, whereas right panels (B, D) were predicted using only the M2 and K1 constituents.

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